

SPLINE-LOCKING SCREW FASTENING STRATEGY (SLSFS)

John M. Vranish
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

ABSTRACT

A fastener has been developed by NASA/GSFC for efficiently performing assembly, maintenance, and equipment replacement functions in space using either robotic or astronaut means. This fastener, the "Spline-Locking Screw" would also have significant commercial value in advanced manufacturing. Commercial (or Department of Defense) products could be manufactured in such a way that their prime subassemblies would be assembled using Spline-Locking Screw fasteners. This would permit machines and robots to disconnect and replace these modules/parts with ease, greatly reducing life cycle costs of the products and greatly enhancing the quality, timeliness, and consistency of repairs, upgrades, and remanufacturing.

The operation of the basic Spline-Locking Screw fastener will be detailed, including hardware and test results. Its extension into a comprehensive fastening strategy for NASA use in space will also be outlined. Following this, the discussion will turn towards potential commercial and government applications and the potential market significance of same.

INTRODUCTION

In space operations, fastening problems are unusually important. Common machine screws cannot be applied with the same ease as on earth; they cross-thread easily because the astronauts must wear gloves and space suits when performing maintenance. Robots have cross-threading problems and more. At the same time, the violent vibrational and loads environment generated by launching payloads into orbit mandates a requirement for strong, simple, light-weight, reliable fasteners that must be met. The Spline-Locking Screw, described in this paper addresses this problem directly. But, in developing what amounts to a screw that cannot be cross-threaded, it soon became apparent that more was involved. One could add alignment and torque reaction pins and accomplish precision and reliable electrical connections in addition to the fastening by making slight modifications to the basic Spline-Locking Screw. A few modifications more and a Standard Robot End Effector and related Astronaut Hand Power Tool emerged. This Standard Robot End Effector (or Astronaut Hand Power Tool) could acquire other power tools or store them in holsters as required. It thus became clear that, using this approach, any number of complex (or simple) tasks could be accomplished in sequence by progressively modifying a basic Spline-Locking Screw system. The purpose of this paper is to provide an introduction to the Spline-Locking Screw concept and its derivative devices and to give an indication of its potential for a comprehensive fastening strategy ; both for space and commercial applications.

A "proof-of-principle" prototype of a foot to fasten the "Flight Telerobotic Servicer" (FTS) robot to Space Station structure based on the Spline-Locking Screw concept has already been built and tested (Fig.1). The results of this effort have immediately shown success and the device has been adopted by the prime contractor and NASA as the foot that will be employed on the FTS robot when it is developed for flight. This particular device, known in NASA as the Workpiece Attachment Mechanism/ Workpiece Attachment Fixture (WAM/WAF) (see Fig. 1) does electrical connections in addition to basic fastening. It will also, of course, permit a robot to walk on a space structure.

THE SPLINE-LOCKING SCREW

In this section the evolution of the old NASA fastener used when repairs in space were anticipated will be outlined along with the problems this evolution caused. This will set the stage for the development of the basic Spline-Locking Screw concept.

The evolution of this NASA fastener [1] is shown in Fig. 2. [Many of these lessons were learned as part of the Solar Max satellite repair mission of 1982]. Screws with low pitch machine threads had been used

successfully many times in space launch operations. But; these would cross-thread when the Astronauts tried to fasten them while wearing gloves and space suits. A guide was added to the screw and this helped; but not enough. Next, the low pitch machine thread was changed to a more high pitch acme thread. This worked; but now the screw would back out during vibrational tests simulating launch. To overcome this, a taper interface at the top of the screw was added. At this point everything worked. However, the additions added a great deal of friction to the system and this meant that large torques on the order of more than 100 ft-lbf. would be required to free up the bolts used in the Solar Max mission. This, in turn, meant that very large and clumsy hand tools had to be used and the Astronauts (or robots) could be subjected to dangerously large torques and forces. For a robot, the situation was nearly impossible. Using the large tools would severely limit robot dexterity. On the other hand, the existing robot End Effectors could only produce 20 ft-lbf. torque[2].

The Spline-Locking Screw was developed by returning to the common machine screw and taking a fresh approach[3,4]. It was decided to cut the bolt in two and leave the bottom half threaded (Fig. 3a.). A new interface was created in the shaft of the bolt. Thus, we have the bolt head (or Driver) and the Object which is normally pinched by the screw system on one side of the interface and the Bolt and the threaded Fixture, it screws into, on the other. The problem, then, was to create an interface that would complete the system. A Spline -Locking type interface (Fig. 3b.) was chosen because it was simple, direct and effective. There is an increase in size; but it is minimal. The operational concept of the system is shown in Fig. 4. The Driver is inserted into the Bolt such that the Male Splines of the Driver fit into matching Female Splines of the Bolt. The Driver is then turned clockwise to tighten the screw system. During this process, the male Driver Spline engages in the female Bolt Spline, it cannot be pulled out and the Bolt and Driver turn together as a single complete machine screw. To unfasten the system, the Driver is turned counter-clockwise, the screw loosens and the Driver Splines relocate in the Bolt (disengage) such that the Driver can easily be pulled out of the Bolt. The Splines are very coarse so they can be designed to seat and fit together such that cross-threading is virtually impossible. And the Bolt is never unthreaded, thus, we have, in effect, a machine screw that cannot cross-thread. At the same time, it is now possible to use low pitch machine threads so large preload forces can be generated from minimum input torques (on the order of 8 ft-lbf. to generate 1,000 lbf. preload). And, these Bolts would not shake loose during launch because of their low pitch. Also, robot End Effectors and Astronaut Hand Power Tools could now be made more modest in size and power, enhancing safety for the Astronaut and safety and dexterity for the robot.

As a practical matter, the Spline -Locking design requires careful and detailed treatment. This is to make certain that the Splines engage and disengage properly and that the payload remains attached either to the Robot End Effector (or Astronaut Power Hand Tool) or to the Fixture at all times to prevent it drifting off into space. We will begin examining these details by following the Tightening sequence of steps shown in Fig. 5a. When the Driver encounters the Bolt, it normally initially comes to rest on the top of the Bolt. As the Driver is rotated clockwise, it rotates with respect to the Bolt until the Driver and Bolt Splines line up; the Driver Bias Spring pushes the Driver into the Bolt (Driver Spline Insertion, Fig. 5a) and the Driver is seated in the Bolt. This raises a question as to how we can be certain the Bolt will not turn with the Driver and prevent the relative motion of the male and female Splines essential to insertion and seating. This is accomplished by adding a Preload Spring to the Bolt (Fig. 3b) to ensure that the Bolt will not turn until the Driver Spline drops into the Bolt Spline, is seated and the "Splines Engaged" (Fig. 4b and Fig. 5a). At this point the Driver torque will simply overcome the friction from the Preload Spring and the Driver and Bolt will turn together. With the Driver and Bolt turning clockwise together, the Bolt will translate downwards and apply a large Locking Force between Driver and Bolt Splines. A subtle distinction is involved between the terms "Spline Engagement" and "Spline Locking" which can be seen by comparing Figs. 4 and 5 and noting that an Underhook Region has been added to the female Bolt Splines. The reason for the Underhook region will be made clear below.

The details of loosening will now be discussed (Fig. 5b). The sequence starts with the Splines locked together and the Object preloaded to the Fixture (Fig. 3). As the Driver is turned counter-clockwise, the Bolt Spline is held in the Driver Spline by the Underhook (Fig. 5b). Thus, the Bolt and Driver must turn together to break the Bolt Thread loose and to release the preload force. As the counter-clockwise rotation continues, the Driver remains in its downward position because of its Preload Spring, but the Bolt translates upwards (Fig. 5b). This causes the Splines to unlock and reposition for Spline Disengagement and Removal. As the Bolt translates upwards, it is capable of generating a large force to "push" the Object away from the Fixture. This condition is termed "Push-Off" and prevents cold welding or jamming of the

Object to the Fixture. At this point, the Driver and Bolt turn together until the Bolt threads hit a stop. The Driver Splines and the Bolt Splines remain aligned throughout for easy removal of the object from the Fixture. Some of the reasons for the Underhook Region now begin to emerge. This addition makes certain that, during the unfastening process, the Bolt is located in the Fixture in the same position each time before the Driver and Object can be removed. This also makes certain that the Bolt and Driver are properly positioned to begin the Insertion and Fastening process shown in Fig. 5a.

ELECTRICAL CONNECTOR CAPABILITY

In this section, it will be shown that an electrical connection capability can be added to the fastening capability by adding minor modifications to the basic Spline- Locking Screw[4]. Further, it will be shown that this leads to an entirely new set of devices to include End Effectors with Tool Storage and Tool Autochanger capabilities, the WAM/WAF and an Astronaut Power Hand Tool.

An electrical connector capability can be incorporated in the Spline- Locking Screw concept as shown in Fig. 6. The Spline-Locking Screw Bolt would be threaded on a Nut rather than into the Fixture. The Bolt is

coupled to the Fixture by means of a Preload Spring F^S (nominally 100lbf) forcing the Bolt down towards the Fixture. Contact between the Bottom Stop on the Nut and the Fixture prevents the downward translation of the Bolt. Thus, the Bolt and Nut are preloaded against the Fixture with a force equal and

opposite to that of the Preload Spring (labelled $F^{RS 1}$ in Fig. 6). Also, the interface between the Nut and Fixture are splined so that the Nut cannot rotate; but can translate between the Fixture Top and Bottom Stops. Electrical Pins can be added to the Nut, and Pin Receptors added to the Fixture. In this section, both the tightening and loosening sequences will be examined.

As the Driver turns it first seats in the Bolt and follows all the steps associated with the tightening process

described above through Spline Locking. At this point, the $F^{RS 1}$ force transfers from the Fixture/Nut interface to locking the Driver and Bolt Splines together (shown as F^D in Fig. 6). The F^D force, in turn, is reacted by the equal and opposite force (labelled $F^{RS 2}$ in Fig. 6 forcing the Fixture against the Object. All the above forces (F^S , $F^{RS 1}$, F^D , and $F^{RS 2}$) are equal to each other. They are given different subscripts because they exist at different times and at different locations in the fastening sequence. As the Driver continues to turn clockwise, the Bolt turns with it and, since the Bolt cannot translate downwards, being held in place by the Locked Splines of the Driver and Bolt, and the Nut cannot rotate, the Nut translates upwards. Throughout this process, the force sustaining the Spline- Locking remains constant and equal to that of the Preload Spring. And, The Object and Fixture are forced against each other with the same force. We thus, have a new condition which will be termed **Hard Dock**. With the proper Alignment Guides on the Fixture and Object (not shown in Fig.6), proper preconditions have been achieved for the electrical connection. As the Driver continued to turn clockwise, the Nut translates upwards until a precision electrical connection is made. Shortly afterwards, the Nut hits its Top Stop on the Fixture. With Nut translation stopped, the Bolt once again attempts to translate downwards. This forces the Object and Fixture together with preload forces. This condition is termed **Preload**. Once again, it should be noted that Spline Locking can be done in either a **Hard Dock** or **Preload** condition, depending on the circumstances. Both conditions are useful in ensuring that the Object is properly secured to the Fixture throughout the Fastening process. It is also, perhaps, appropriate to note that the Object is secured (or Docked) to the Fixture as soon as the Splines are Engaged Fig. 5a), prior to Hard Dock. However, there is rattle between the Object and the Fixture during this condition so we will describe it with the term **Soft Dock**.

Turning the Driver counter-clockwise reverses the steps described above and disengage the Object and the Fixture as well as the Driver and the Bolt. As previously described, under Hard Dock and Preload conditions the Driver Spline is seated in a groove in the Bolt Spline (Fig. 5). As described above, during counter-clockwise rotations, the Bolt Spline Underhook provides an interference obstacle preventing the two Spline Sets from slipping out of engagement. It should be noted, that during the disengagement of the Electrical Connectors, the Bolt Preload Spring provides the disengagement force and the force holding the Splines in Lock (and Hard Dock) is the difference between the Bolt Preload Spring force and that used in pulling the Electrical Connectors apart. And, this Hard Dock condition remains until the Nut bottoms and the Bolt

translates upwards, taking the system out of Hard Dock, unlocking the Splines, and into Soft Dock. Again, during this transition from Hard Dock to Soft Dock, the Bolt translates upwards and pushes the Fixture and the Object slightly apart (say 0.060 in.). This condition is termed Push- Off. The Bolt Spline is now free of the Under Hook and so the Driver Spline rotates with respect to the Bolt Spline until it hits a stop and both Driver and Bolt are stopped. This forces the two Splines to be lined up such that they can easily and reliably be pulled apart.

DERIVATIVE DEVICES

It would now be possible to make further minor modifications to the Spline- Locking Screw and produce a range of useful devices. One such device would be a combination Special Tool Interface and Autochanger [5]. This is a straightforward extension of the arrangement shown in Fig. 6. The Object of Fig. 6 can be fastened to a robot wrist and a motor splined to the Driver. This Coupling between Motor and Driver would include a Compliant Spring to permit the Driver to be pushed up out-of-the way. This arrangement of Object, Electrical Pin Receptacles, and Compliant Driver with Motor would constitute a Standard End Effector. Alignment Pins would be added to the Fixture (which would also serve as the Special Tool Interface) and Mating Receptacles would be incorporated in the Standard End Effector. Any Special Tool could be fastened to the Interface and the robot. Thus the robot could use the Standard End Effector to mate with and fasten to a common Special Tool Interface. And, since any Tool could be attached to the Special Tool Interface, and power and signal provided, the robot could acquire and use any of a wide variety of Tools. It should be noted that the mating procedure by which the robot acquires a Special Tool would use standard practice. That is, alignment is standard "peg-in-the-hole" using alignment pins and mating receptacles. (The WAM/WAF (Fig. 1)[4] is essentially a large version of this device which has the strength to withstand torques and forces on the robot leg.) The bottom of the Nut can be used to pinch tabs of a Tool Storage Holster and there by store Special Tools[5]. This system would be equally effective on earth or in Zero or micro "g". Thus the system would become its own Autochanger. Although not shown in this paper, a similar approach could be taken in permitting a robot to use "Spline-Locking Screw" techniques to release and fasten payload boxes known in NASA as Orbital Replacement Units (ORU)[6].

CALCULATIONS AND TEST RESULTS

A WAM/WAF prototype (Fig. 1) was constructed and tested as a first prototype. The prototype has been tested and demonstrated on a robot and found to dock, and to go through its proper fastening sequence of Soft Dock, Hard Dock, Electrical Connections (to include actuating dust covers on both WAM and WAF), and to provide Preload Forces sufficient to allow the robot to wave a large steel table around with impunity. Without question, it has great holding strength with minimal motor torque required. More detailed testing is being conducted in the Goddard Space Flight Center robotics lab. Calculations indicate that the WAM/WAF can produce excellent preload forces with modest actuation torques.

$$dW_{in} = dW_{out} + dW_{losses} \quad (1)$$

$$dW_{losses} = \text{friction losses in bolt and in reaction thrust bearing}$$

$$T(\theta)d\theta = F(\theta)\left\{\frac{d\theta}{2\pi L} + u_{s1}R_1d\theta + u_{s2}R_2d\theta\right\} \quad (2)$$

$$T(\theta) = F(\theta)\left\{\frac{1}{2\pi L} + u_{s1}R_1 + u_{s2}R_2\right\} \quad (3)$$

Where:

dW_{in} = differential work done by the Driver on the Bolt .

dW_{out} = differential work done by the Bolt as it translates.

dW_{losses} = friction losses in Bolt and in reaction thrust bearing during differential work.

$T(\theta)$ = input torque.

$F(\theta)$ = Bolt preload.

u_{s1} = Nut - Bolt friction coefficient = 0.15.

u_{s2} = coefficient of friction of rolling friction = 0.008 .

R_1 = Bolt radius.

R_2 = radius of thrust bearing.

$d\theta = d$ if differential twist angle.

L = Bolt thread lead .

Thus a 0.75 in UNF 16 bolt producing 1000 lbf preload requires < 6.5 ft-lbf input torque which is a very modest value.

We will now examine the efficiency of the system.

$$E = \frac{dW_{out}}{dW_{in}} \quad (4)$$

$$E = \frac{F(\theta)}{2\pi LT(\theta)} \quad (5)$$

For the bolt, preload and coefficient of friction listed above, we get an efficiency of 12.8% which is more than satisfactory.

The WAM/WAF will not back drive and hence a brake is not required.

$$\tan(\gamma) = \frac{1}{2\pi LR_1} \quad (6)$$

Where γ = Bolt lead angle.

When $\tan(\gamma) < u_{s1}$ system will not back drive.

$$u_{s1} 2\pi LR_1 = \text{safety factor} \quad (7)$$

For our WAM/WAF, we get a safety factor > 5 so clearly a brake is not required.

COMPLEX ELECTROMECHANICAL SYSTEMS

A few more simple modifications can be added to the Locking Spline Screw to produce a multi-rotational output[7] which can be monitored by electronic signals throughout the process. This capability will, in turn, form the basis for using Locking Spline Screw techniques to operate complex electromechanical systems. Once again, some events must be done serially. During the process in which the robot acquires the Object, we have a sequence of: mating ; Soft Dock; Hard Dock; Electrical Connections; Multi-Rotational Output until a Stop is reached and the Object is released to the custody of the robot; then, finally, Preload. During the process in which the robot fastens an Object to some Fixture, we have a sequence of: Release of Preload ; Hard Dock; Multi-Rotational Output until a Stop is reached and the Object is fastened to a Fixture; Release of the Electrical Connectors; Soft Dock; Push Off of the robot Standard End Effector from the Object; and Separation of the robot Standard End Effector from the Object. It is apparent that with multiple rotations available from an output shaft which will turn until it reaches a stop, any number of different types of electromechanical systems can be driven by the shaft including items as complex as clocks. We would have, then, what amounts to a portable motor, controller, power supply, and system software and electronics and mechanical interfaces. All that most particular applications would require is an embedded mechanical system and sensors. This would vastly simplify many tasks. And, in those instances where an embedded motor is still required, the robot could supply power and controls.

SMALL OBJECTS

The examples above have shown that there is virtually no limit to the complexity of tasks that can be done by the Spline-Locking Screw system. This system could also handle extremely Small Objects (2 in.X2 in.X1.5 in.)(5 cm.X 5cm. X 3.8 cm)[6]. Handling Small Objects in space would be more formidable than is commonly realized. The main problem is the micro "g" environment that requires that every Object be fastened to something or it will float away (or worse-accelerate to missile-like speeds). This requires that control be fastidiously maintained during each step of the hand-off process despite the small size of the Object and the required simplicity of the fastening scheme. Adding to the difficulty is the requirement that the small object be grasped by the Spline-Locking Screw Standard End Effector". The problem can be

solved by piercing the Small Object with a Bolt, one end of which is a Driver interface and one end of which is the Bolt Spline (female) interface which mates with the Driver of the Standard End Effector. A small Rotating Socket with compliant spring would be embedded into the Fixture. Alignment Tabs would be placed in the Object, the Robot End Effector and the Fixture to permit the Small Object to be properly aligned in rotation at all times. The Bolt would be threaded into the Small Object so that as the Robot Driver turned, the Small Object Bolt would turn and translate up or down and, in the process, screw the Object off the End Effector and on to the Fixture or off the Fixture and on to the End Effector as required. The Small Object would be in proper control at all times.

FASTENING STRATEGY FOR SPACE OPERATIONS

The discussion above has shown the unusual capabilities of the Spline- Locking Screw approach. Further, it is clear that this fastener could form the basis for performing a host of operations ranging from attaching small, simple objects to acting as a transportable motor/control system/power supply and systems interface for complex electromechanical systems to permitting a robot to walk on a space structure or handle tools with the same appendages as the case may be. And, all of these devices could be actuated by the same rotary Driver (Identified as The Robot End Effector when used with robots or the Power Hand Tool when used by Astronauts). It would seem that a proper frame work has been laid for a comprehensive fastening strategy in which Spline-Locking Screw mechanical and electrical interfaces can be standardized into a few size ranges (like industrial machine screws) and any of a number of applications, techniques and innovative designs could be implemented consistent with those interfaces. Parts counts on space craft would be drastically reduced, modularity would be enhanced and maintenance and repair greatly facilitated. Robotics could now be employed more extensively in assembly and maintenance operations and Astronauts would also find things simplified and safer.

COMMERCIAL APPLICATIONS

Humans using their bare hands do not normally cross-thread bolts. Thus, from an industrial stand-point, Spline-Locking Screw would be another of many available fasteners serving a small, but important, niche' market , typically involving bolts of 0.5 in. dia. or larger in which the object they are fastening must be periodically removed and replaced using power tools. With these larger bolts, threads are coarse, the torque involved in installing them is large and, because of their size, Locking Splines can easily and cost effectively be employed. Because fine machine threads could be used with the Spline-Locking Screw, required torque would be reduced and with it the size of the power tools and objects would be held more securely against working their way free during vibration. Also, because the Spline-Locking Screw Bolt is pre-threaded, attachment is very quick; just a few turns. In the airline industry, for example, aircraft engines could be dropped quickly , overhauled and remounted. Similarly, the avionics would be installed using the Spline-Locking Screw with electrical connector. This, in turn, suggests that the computer industry could make extensive use of Spline-Locking Screws with electrical connectors. Earth moving and materials handling equipment could profitably use such fasteners extensively as could the automotive industry (wheel lug nuts and engine and transmission mountings come to mind immediately). Military applications are particularly attractive. Military aviation has all of the problems associated with civilian aviation; but on a more pressing schedule and requiring field maintenance. Tank and military automotive needs would also be pervasive.

SUMMARY/CONCLUSIONS

The Spline-Locking Screw presents a unique and fundamental building block to facilitate assembly and maintenance in space (micro "g"). Screw fastening , so pervasive on earth, could now be employed in micro "g" without danger of cross-threading by Astronauts in space suits or by robots. This would advance the capability of assembly, maintenance and materials handling in a fundamental sense. Further, by allowing standardization and modular construction on a here-to-for unprecedented scale, Spline-Locking Screws would simplify logistics; a consideration which is of special import in space.

The concept, while new, is straight forward. Indeed, Goddard Space Flight Center has already successfully constructed and demonstrated a Workpiece Attachment Mechanism/Workpiece Attachment Fixture (WAM/WAF) for the Flight Telerobotic Servicer (FTS) and End Effector Spline-Locking Screw prototypes for fastening payload boxes are in construction.

Commercial possibilities for this concept fall into an impressive market niche' , particularly for Bolts 0.5 in. dia. or larger. These include: 1. civilian aviation maintenance and overhaul, mechanical systems and avionics. 2. The computer industry. 3. Earth moving and materials handling systems. 4. The Automotive

industry. 5. Military applications in general with aviation, avionics and tank and automotive support in particular.

REFERENCES

1. **Portion of Shop Drawing #GL 1087209, Rockwell International Corp. Space Division**, dated 9/7/76 showing the operation of an ACME Screw Payload Fastener for the Solar Max repair mission of 1982, courtesy of Robert Davis, NASA/GSFC.
2. **FTS End Effector End Item Specification** dated 1990, courtesy of Paul W. Richards, NASA/GSFC.
3. **Invention Disclosure : SPLINE-LOCKING PAYLOAD FASTENER** by John M. Vranish GSFC dated 8/10/90, Case no. GSC 13,378-1, filed 6/5/91.
4. **Invention Disclosure: WORK ATTACHMENT MECHANISM/WORK ATTACHMENT FIXTURE (WAM/WAF)** by John M. Vranish GSFC dated 2/25/91, Case no. GSC 13,430-1.
5. **Invention Disclosure: SPLINE SCREW AUTOCHANGER** by John M. Vranish GSFC dated 3/26/91, Case no. GSC 13,435-1.
6. **Invention Disclosure : SPLINE-LOCKING PAYLOAD FASTENING SYSTEM** by John M. Vranish GSFC dated 8/10/90, Case no. GSC 13,454-1.
7. **Invention Disclosure: SPLINE SCREW MULTIPLE ROTATIONS MECHANISM** by John M. Vranish GSFC dated 6/3/91, Case no. GSC 13,452-1.